A review of photovoltaic module technologies for increased performance in tropical climate

Osarumen O. Ogbomo[1*], Emeka H. Amalu[2], N.N. Ekere[1], P. O. Olagbegi[3]

[1]School of Engineering, Faculty of Science and Engineering, University of Wolverhampton, WV1 1LY, UK

[2]Department of Mechanical, Aerospace and Civil Engineering, School of Science and Engineering, Teesside University, Middlesbrough, Tees Valley, TS1 3BA, United Kingdom.

[3]Mechanical Engineering Department, Faculty of Engineering, University of Benin, Nigeria

[*]Email: O.O.Ogbomo@wlv.ac.uk, ogbomoosarumen@yahoo.com; Tel.: +44(0)7471372448

Abstract

The global adoption and use of photovoltaic modules (PVMs) as the main source of energy is the key to realising the UN Millennium Development Goals on Green Energy. The technology - projected to contribute about 20% of world energy supply by 2050, over 60% by 2100 and leading to 50% reduction in global CO_2 emissions - is threatened by its poor performance in tropical climate. Such performance discourages its regional acceptance. The magnitude of crucial module performance influencing factors (cell temperature, wind speed and relative humidity) reach critical values of 90°C, 0.2 m/s and 85%, respectively in tropical climates which negatively impact module performance indices which include power output (PO), power conversion efficiency (PCE) and energy payback time (EPBT). This investigation reviews PVM technologies which include cell, contact and interconnection technologies. It identifies critical technology route(s) with potential to increase operational reliability of PVMs in the tropics when adopted. The cell performance is measured by PO, PCE and EPBT while contacts and interconnections performance is measured by the degree of recombination, shading losses and also the rate of thermo-mechanical degradation. It is found that the mono-crystalline cell has the best PCE of 25% while the Cadmium Telluride (CdTe) cell has the lowest EPBT of 8-months. Results show that the poly-crystalline cell has the largest market share amounting to 54%. The CdTe cell exhibits 0% drop in PCE at high-temperatures and low irradiance operations – demonstrating least affected PO by the conditions. Further results establish that back contacts and back-to-back interconnection technologies produce the least recombination losses and demonstrate absence of shading in addition to possessing longest interconnection fatigue life. Based on these findings, the authors propose a PVM comprising CdTe cell, back contacts and back-to-back interconnection technologies as the technology with latent capacity to produce improved performance in tropical climates.

Keywords

photovoltaic modules; solar cell technology; contact technology; interconnection technology; energy payback time; power conversion efficiency; fatigue life.

1. Introduction

The annual electrical power consumption of the entire planet can be generated by the sun in just one hour [1]. Thus, solar energy is abundant in addition to being clean, sustainable and renewable [2], [3]. Surprisingly, some parts of the world are still struggling to meet their energy needs. It may suffice to say that the regions experiencing energy issues may be having energy conversion problems rather than energy supply problems [2], [4]. It is projected that if 100% exploitation of the energy potentials of the sun can be achieved, the world would cease to have energy crises [2], [3]. The photovoltaics are currently poised to be the promising technology to be used to harness this energy – though at reduced efficiency. The performance of a PV module can be characterised by its power output (PO), power conversion efficiency (PCE) and reliability [5]–[8]. The PO measures the capacity of the module and the amount of electricity (in watts) it can generate. On the other hand, the PCE quantifies the percentage of power generated by the module in comparison with the total solar energy available to the module. Thus, a module may generate more power than another module but possess a lower PCE. Generally, module reliability measures the probability that it will perform the intended function over a specified interval under stated conditions. Therefore, mean-time-to-failure (MTTF) and cycle to failure are terms associated with the rate of failure of PVMs and thus used in its reliability measurements [9], [10]. The major components of a PV module are the cells, contacts and interconnections. These components are selected for investigation because they are known as the key determinants of module performance as well as the failure mode [11]. The overall performance of a PV module is dependent on the individual performances of the components.

Ambient conditions significantly influence the level of performance of PV modules. These are the intensity of solar radiation, cell temperature, wind speed and humidity [12]–[14]. PV modules are designed to operate under standard test conditions (STCs). The conditions are: solar radiation of 1000 W/m^2, cell temperature of 25 °C, wind speed of 1 m/s and air mass (AM) of 1.5. These STCs are different from actual operating conditions which vary with climatic zone [15]. This review focuses on the tropical climate. The zone is characterised by high-temperature and humidity, high density of tall trees and vegetation, heavy cloud cover and high rates of precipitation. High precipitation produces cloudy skies and more shades on some days of the year. The high-temperatures range from 18 to 40 °C and forces the PV cell temperature to rise up to 90°C. The relative humidity is in the range of 35% to 85% with wind speeds of 0.2 m/s and lower [12]–[14],[15]. Consequently, PV modules operating in the tropics possess higher failure rates than those in temperate climates. The failure modes observed in the field include delamination and discolouration of EVA, solder bond and ribbon degradation and cracking as well as burn marks [11], [16], [17]. Since the tropical climate ambient significantly deviates from the STCs, further research aimed at providing more information is needed to predict the performance of PV modules in the climatic zone[18]–[23] accurately.

A number of researches have focused on the performance of PV cells in tropical climatic conditions [24]–[29]. Ike C.U [24] in his study, investigated the effect of ambient temperature on the performance of PV modules in Nigeria tropical climate. His results show an indirect proportionality between ambient temperature and power output. He reported that PV modules in the test region demonstrated high PO at low ambient temperatures while the reverse is the case at high ambient temperatures. Mekhilef et al [28] in their study, investigated the individual and combined effect of dust, humidity and air velocity on the efficiency of photovoltaic cells. They reported that USA demonstrated 1-4.7% reduction in PCE in a two month period, 32-40% reduction for 6-8 months period in Saudi Arabia, 17-65% reduction over 38 days in Kuwait, 33.5-65.8% reduction over for 1-6 months period in Egypt and 11% reduction in Thailand. These findings indicate the poor performance of PV cells in tropical climate. They indicated that humidity and dust deposition resulted in low heat dissipation and shading respectively hence PCE reduction while increased air velocity improved PCE. Ndiaye et al [27] investigated the degradation of PV modules in the Senegal tropical climate. They focused on the degradation of short circuit current (I_{sc}) and open circuit voltage (V_{oc}) which translate to PO and PCE. They reported a 13% and 11% reduction in I_{sc} and V_{oc} respectively over a ten month period. Although Ike, Mekhilef, Ndiaye amongst other researchers in their respective studies have investigated the performance of PV modules in tropical climate, they have not carried out wide spread researches as their results are solely based on the mono crystalline silicon PV cell. Our study, however, aims to review available PV cell technologies: commercially available and state-of-the-art, as will be thoroughly discussed in section 2 of this paper.

Walsh et al [25] in their study , proposed an optimised PV module for the Singapore tropical climate. They highlighted the poor performance of some commercial PV modules under the Singaporean climate. Their optimised PV module was developed by making material changes in glass, encapsulant and back sheet parts of the conventional PV module. Their aims to reduce reflection and increase the surface area exposed to radiation led to changes in glass material, increased radiation transmittance led to encapsulant change while increase in thermal conductivity resulted in change in back sheet material. However, there were no changes to the PV cell material, type of contact or interconnection technologies hence no mention of PCE, PO and reliability which are the measures of PV module performance. These, amongst other gaps were identified by our study. In order to promote robustness, increase reliability and all round improved performance of PV modules in tropical climate, this paper proposes model of PV module which includes the cell, contacts and interconnection technologies as will be discussed in sections 2, 3 and 4 respectively. There has been no such research which dissects the major parts of the PV module so as to identify the particular technologies which demonstrate best performance in tropical climate.

Cost has been identified as an important factor in the choice of energy sources especially in the developing countries. In order to increase the adoption of the module globally and especially by the developing countries, the cost has to be as low as possible. It is basic experience that cost determines the choice of energy for the individual, company, community or nation. Figure 1 presents a chart with plot of cost of different energy sources in USD ($) which also applies for any mention of cost in this paper. It can be seen in the plot that the cost of energy from PV (solar) is highest. Currently, the fossil fuels cost

$0.50/W while the cheapest PV modules cost $0.75/W [30]. It is pertinent to mention that there has been urgent, aggressive and on-going research to reduce the cost of PV modules as well as the energy payback time (EPBT) while increasing the net energy ratio (NER) of the cells. The trend of the achieved cost reduction is depicted in Fig. 2. However, despite the progress, people generally choose fossil fuels because they are cheaper while neglecting the detrimental environmental effects [31].

A plot of the quantity of greenhouse gases (GHG) emitted by different electricity generation sources is presented in Fig. 3. The plot shows that GHG emission by Solar PV is about 7.95% of the quantity emitted by Lignite – which has the largest quantity of emission.

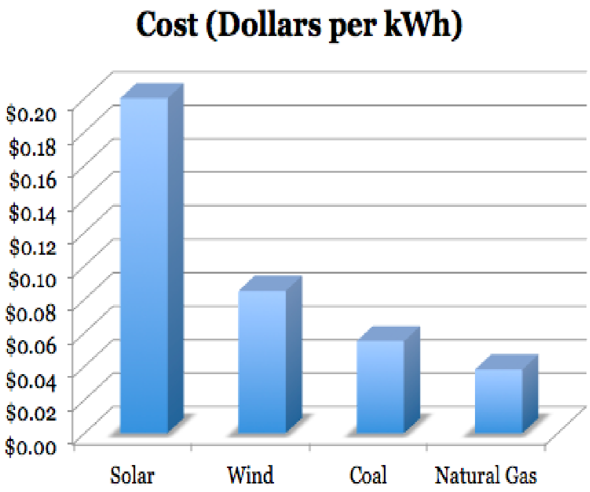


Fig.1: Price comparison of energy sources[161]

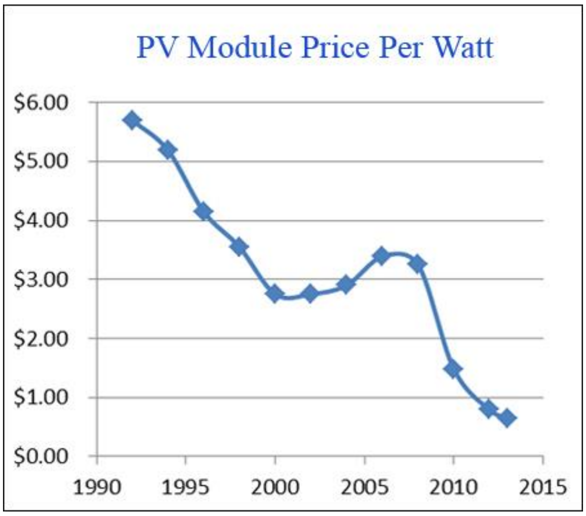


Fig. 2: PV module price over time[160]

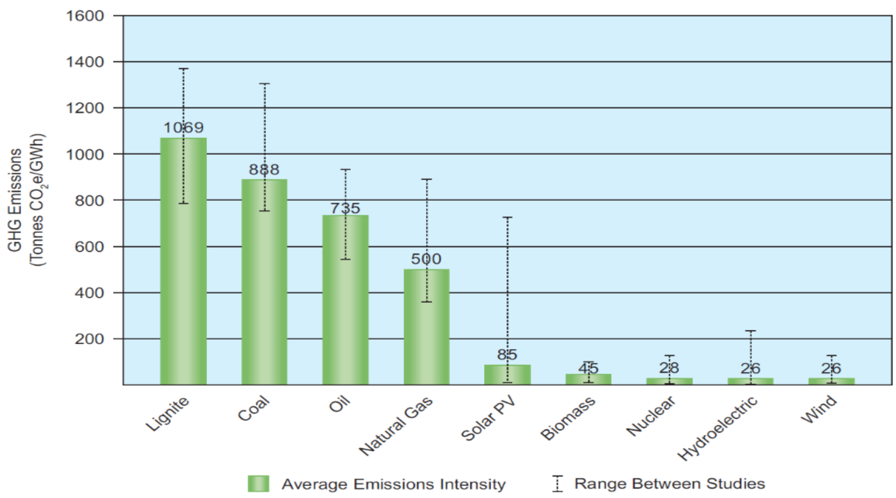


Fig.3: Comparison of CO_2 emissions of electricity generation sources [162][163]

Figure 4 depicts the plot of world energy consumption from 1990 to 2012. It shows a significant increase in the consumption of renewables (including hydro) compared to the fossil fuel. To progress this trend, it is proposed that improvement of the performance and reliability of PV module in the tropics would engineer its adoption and usage.

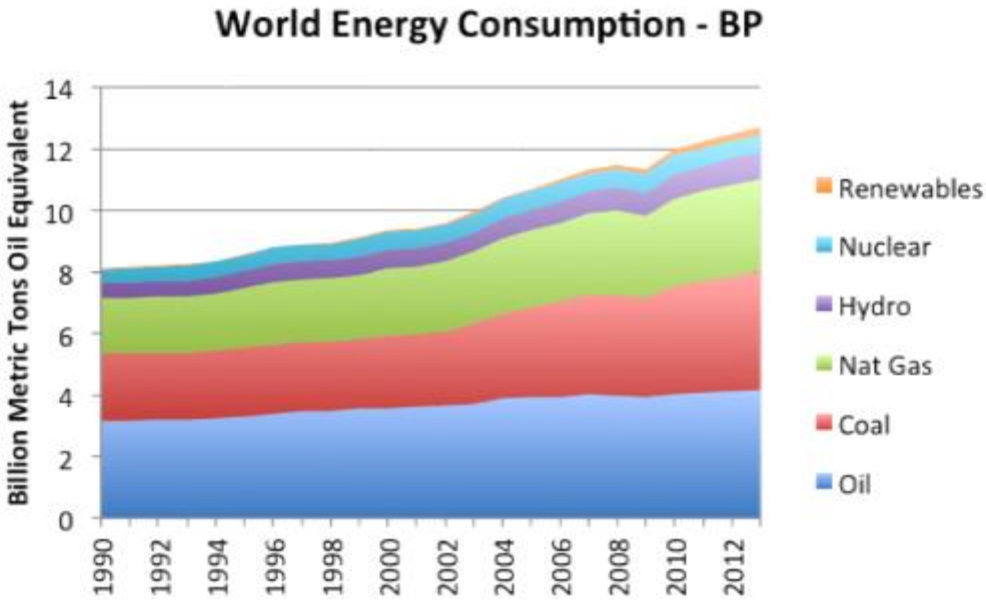


Figure 4: World energy consumption [164]

Most regions in the tropical climate struggle to meet their energy demands. Some of them have less than 40% of their total population with access to electricity [32], [33], [3], [4]. In addition, electricity supply to this region is as unreliable as it is unavailable at most times [2], [33]. PV technology is poised to meet the energy needs of these regions owing to its decentralised, sustainable and renewable nature [2], [3], [34]. However, due to the lower cost of fossil fuels coupled with the poor performance of PV modules in these regions, the fossil fuels have been the dominant energy source. Thus, to engineer adoption and use of the PV technology, modules with improved performance have to be designed and manufactured. To achieve the proposed advancement in the technology, review of the current performance and reliability of PV modules operation in the tropical regions are urgently needed. It has been reported by reference [34] that there is lack of information about this technology with few literatures on its failure mechanisms particularly in tropical regions and hence the low technical knowledge of the systems' operation in the tropical environment.

The aim of this paper is to review photovoltaic module technologies for increased performance in tropical climate. This research seeks to review the cell, contact and interconnection technologies utilised in PV module manufacture. The review will identify the most suitable technology with potentials for producing a robust PV module for improved performance at elevated temperatures.

2. Cell technologies

Fig. 5 presents the schematic of a PV cell assembly while showing the incident sunlight. The cell and the contact technologies of the assembly can be seen. This section presents and discusses a review of the different cells utilised in PV assembly. Its objective is to identify the cell(s) that the usage in manufacture of PV assembly will produce robust module with improved performance in hot climate. With the current recorded value of maximum power conversion efficiency (PCE) of PV cell at 45%, there is a strong belief that this value can be improved drastically in the near future considering the huge on-going research in this direction.

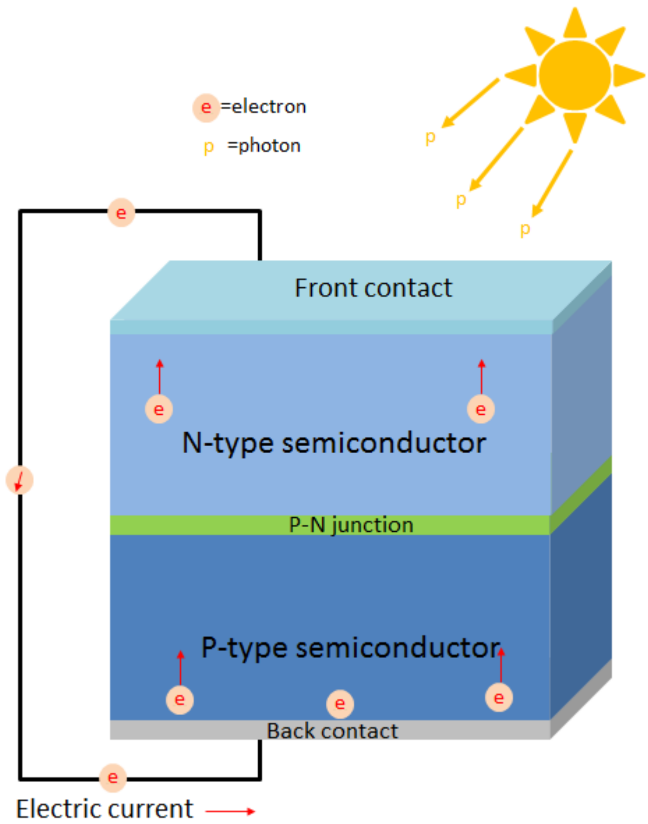


Figure 5: Component parts of a typical PV cell

A PV cell is made of semiconductor materials that remain electrically neutral until excited by the solar energy [35], [36]. Exposure of the semiconductor material to photons forms electron-hole pairs in the material [37]. Different PV materials have different energy band gaps which characterise their absorption capacity. Photons with energy equal to the band gap energy of the PV cell material are absorbed to create free electrons while photons with less energy than the band gap energy pass through the material. On the other hand, photons that possess higher energy than the band gap energy release excess energy in the form of heat as they are absorbed [38], [39], [40]. Advancement of this technology has been challenged by improvement of the absorption capacity of the materials and thus the conversion efficiency of PV cells. It has therefore necessitated and supported continuous and consistent research and development focused on identification of materials which possess wide energy band gap to be used as PV cells. Fig. 6 presents the market share of the six common PV cell materials. It can be seen in the Figure that poly-crystalline silicon demonstrates having the highest share with value of 54%.

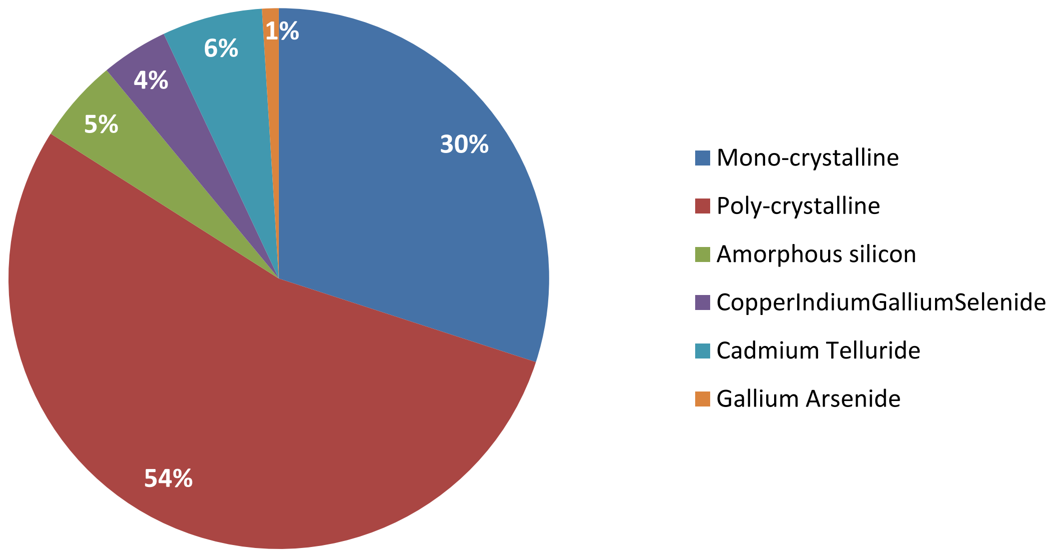


Figure 6: Market share of PV cells (%)

Sections 2.1, 2.2 and 2.3 discuss the past, present and future of PV cell types and materials. The sections seek to identify the particular PV cell type and material that the employment in PV manufacture will produce modules with increased overall operational performance in the tropics.

2.1 Crystalline silicon PV cells

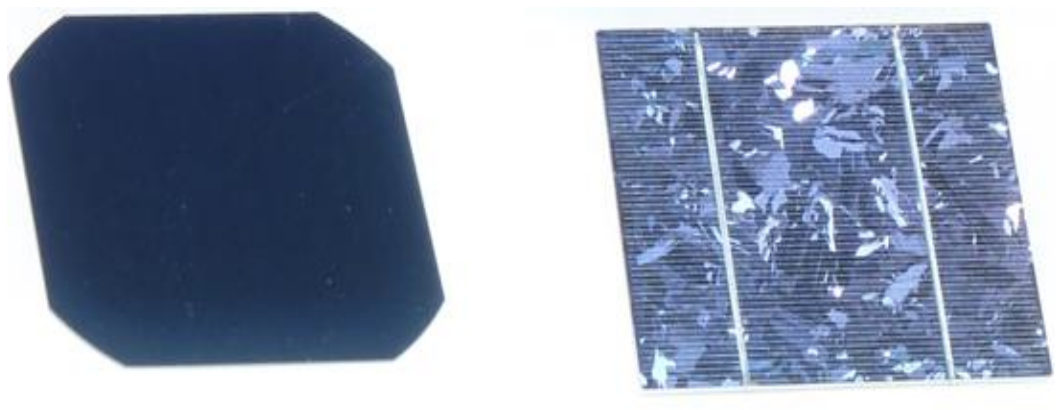
These cells are referred to as the first generation PV cells because they were developed first as early as the 1950s. They are produced from 100 to 200 µm thick wafers sliced from bulks of solar grade silicon [6]. They are also called conventional or traditional or wafer-based solar cells. The cells could be mono-crystalline (mono-Si) or polycrystalline (multi-Si) in nature depending on the mode of production. Further discussions on the mono-crystalline and poly-crystalline silicon PV cells are presented in subsections 2.1.1 and 2.1.2, respectively.

2.1.1 Mono-crystalline (mono-Si) PV cell

This type of cell has market share of 30% of all PV cells. The share in relation to other cells is shown in Fig. 6. The cell is produced by slicing wafer from a single high purity cylindrical crystal ingot. To optimise cell density, the wafers are cut into octagonal shape. The practice leads to silicon wastage during the manufacturing process [41]. The purity of mono-crystalline silicon cells is very high when compared with that of poly-crystalline counterpart [42]. A measure of the high degree of purity is a homogeneous blue/black colour a single crystal possesses. A single crystal possessing a uniform blue black colouration is presented in Fig. 7(a). The manufacturing procedure of mono-crystalline cell is complicated, sophisticated and expensive – making its price relatively high in comparison with the other cells. It costs about $1.6/W [43], [44] and it may be economical to use the modules in situations that space is the concern. Mono-crystalline cell possess band gap energy of 1.1eV, a PCE up to 25% [45] and energy payback time (EPBT) of 4 years with a designed operational lifetime of 30 years. The cell demonstrates best performance at standard test conditions (STC). However, with a temperature coefficient of power output (p_{max}) at -0.5%, it performs poorly at elevated temperatures [12], [13]. Modules manufactured with this cell show significant reduction in power output (PO) when one of its cells is shaded.

2.1.2 Poly-crystalline (multi-Si) PV cell

Multi-Si cell dominates the PV cell market with a market share of 54%. Fig 6 presents statistics which shows that the cell share is the highest. The technology achieved the highest market share because it experienced accelerated growth in efficiency and decrease in cell cost in recent time. The cells are produced by sawing a square cast block of silicon first into bars and then into wafers. The wafers are square shaped hence less silicon is wasted during manufacturing compared to the production of mono-crystalline cell [41], [46], [47]. The cell consists of small crystals known as crystallites with visible crystal grain. This gives it a metal-flake appearance as seen in Fig. 7(b). The manufacturing process is more cost effective and less sophisticated than that of mono-crystalline PV cell. Its costs about $1.4/W [45], [43], [44]. The cell possesses band gap energy of 1.1eV, a PCE of up to 20%, EPBT of 3 years and operational lifetime of 30years. Polycrystalline cells demonstrate best performance at STC and moderately elevated temperatures. With temperature coefficient of power output (p_{Max}) at -0.5% [12], [13], the cell demonstrates poor performance at high temperatures [43]. The PO of modules manufactured using them decreases when their cell(s) is/are shaded.



(a) (b)

Figure 7: (a) Mono-crystalline PV cell and (b) Poly-crystalline silicon PV cell [165].

2.2 Thin-film PV cell

This type of cell is referred to as second generation PV cell. It is manufactured by depositing one or more thin film layers of photovoltaic material on a substrate such as glass, plastic, ceramic or metal. The thin film layers range from nanometres (nm) to micrometres (µm). Thus, the cell is flexible and light-weight. Fig 8 shows the cell in a flexural loading condition. Thin film cells are less expensive unlike crystalline silicon PV cells which require expensive and sophisticated ingot-growth techniques [48], [49]. Their manufacture consumes less PV material. Thus, its manufacture is cheaper when compared to the first generation PV cells. A thin-film cell cost about $0.75/W [50] on the average. Thin films cells are unlike single-crystal silicon cells that must be individually interconnected in a module. A thin-film device can be made as a single unit - that is monolithically—with layer upon layer being deposited sequentially on a substrate [51]–[53]. Generally, thin film cells demonstrate best performance at high temperatures due to temperature coefficient of power output (p_{Max}) at less than -0.25% [48], [49], [54]. In addition, these cells are very slightly affected by high temperatures and shading [55]–[57].

There are various types of thin film PV cells. The market dominant thin film PV cells are: Amorphous silicon, Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe) and Gallium Arsenide (GaAs). The cells are discussed further in subsections 2.2.1, 2.2.2, 2.2.3 and 2.2.4, respectively.

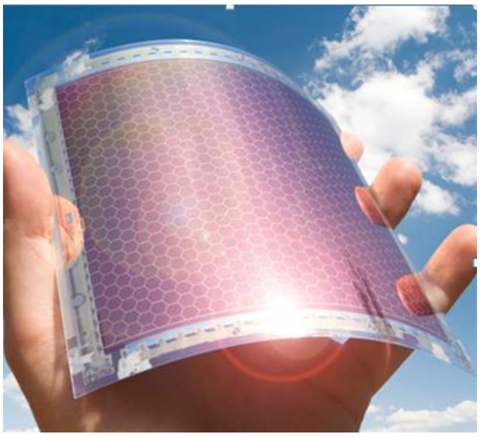


Figure 8: A thin film PV cell under flexural loading [166]

2.2.1 Amorphous silicon (A-Si) PV cell

This is the first thin film PV cell ever made as early as the 1970s. Compared to the crystalline counterparts, the cell is less popular in the market with a market share of 5% as seen in Fig. 6. It is made by sandwiching thin film cell materials of 1 µm thick amorphous silicon between two panes of glass. It possesses band gap energy of 1.7eV [58]. The application of the thin film technology enables amorphous silicon cell to be thinner and cheaper than crystalline cell. Amorphous silicon is known to absorb sunlight more effectively than crystalline silicon [43], [44]. This implies less silicon; about 1/600th of the material required for crystalline silicon cells is used for its manufacture [58]. A-Si PV cell demonstrates better performance than the crystalline cells in shaded conditions [43], [44].

In addition, the cell possesses good heat resistance and thus is more efficient in elevated temperature climate than the crystalline silicon cells. This is due to a temperature coefficient of power output (p_{Max}) of -0.25% [8], [13], [59]. However, modules manufactured using them are more fragile, larger and heavier than the modules manufactured using conventional first generation cells. Consequently, this type of cell is used when space is in abundance. Their application is limited to low power applications [45] because module manufactured using the cell possesses low PCE in the range of 6 to13%. The EPBT is 2 years and operational lifetime is 25 years [45], [6], [8], [43], [59], [50].

2.2.2 Copper Indium Gallium Selenide (CIGS) PV cell

The CIGS thin film PV cell has 4% market share as shown in Figure 6. The cell is made by using vacuuming manufacturing procedure to deposit a thin layer of 2 µm copper, indium, gallium and selenide on glass or plastic backing along with electrodes on the front and back sides. The produced current flows via the electrodes.

Gallium-free variants of the semiconductor material are abbreviated as CIS. The manufacturing cost is lower than the crystalline silicon PV cells but more expensive than other single junction thin film cell like Cadmium Telluride (discussed in section 2.2.3). Over the years, the CIGS cell has been poised to be the promising cell and thus many companies and research institutes took particular interest in it. The companies and institutes drive research geared towards improving the lifecycle reliability, power output efficiency and cost of modules made using the cells [44], [47], [60], [61]. In recent years, the supply of CIGS cells has dwindled causing major manufacturing companies like Nanosolar and Solyndra to be out of business. Companies and research institutes which include Solar Frontier continued to maintain their presence in the PV industry while the hope of CIGS cell bouncing back to the PV cell market in the future remains unpredictable [48], [54]. CIGS has band gap energy of 1.45 eV, a high sunlight absorption coefficient and PCE of 20% as well as EPBT of 1 year [7], [43], [62], [63]. Its performance is slightly affected by shading.

2.2.3 Cadmium Telluride (CdTe) PV cells

Cadmium is abundant in nature because it is a by-product of other industrial metals like zinc. It is a carcinogen with detrimental effects to the kidney and bones. It is one of the six deadliest toxic materials known to man. There are numerous legislation, including the Restriction of Hazardous Substances (ROHS) directive, restricting the use of Cadmium and some other substances because of their hazardous nature [64]–[66]. Although the element is this hazardous, the compound Cadmium Telluride (CdTe) used in PV cells is much more environmentally friendly. CdTe contains ≤7g of elemental Cd in each square metre of PV cell than the average single cell nickel-cadmium battery. CdTe is more stable and less soluble than elemental Cd and so is less toxic [67].The second material, telluride is scarce and as rare as platinum in nature. Telluride increases the price of the CdTe cell.

Presently, CdTe cells amount to about 40% of the thin film PV market and 6% of PV cells as seen in Fig. 6. The manufacturing procedure is simple, cheaper than the crystalline cells and other thin film cells [48], [53]. They are the only thin film material so far to rival crystalline silicon in cost/watt [48], [51], [53]. The band gap energy is 1.5 eV which is optimal for a single junction PV cell [50], [68]. The cell's EPBT which is the lowest of all mass-produced PV technologies can be as short as eight (8) months [43], [69] in favourable locations as seen in Fig. 11. In addition to possessing temperature coefficient of power output (p_{Max}) 0% which implies good performance at elevated temperatures, the PCE can reach up to 21% and the operational lifetime is 20 years [45].

2.2.4 Gallium Arsenide (GaAs) PV cell

GaAs PV cells are made majorly from gallium and arsenic. Gallium is rarer than gold and a by-product of the smelting of other metals - notably aluminium and zinc. Arsenic is not rare, but it is poisonous. However, the compound GaAs is stable and not toxic [70]–[72]. GaAs cells possess band gap energy of 1.43 - 1.7 eV so they can absorb photons with higher energy levels than crystalline silicon PV cells [56], [57], [72]. In addition, GaAs has high absorptivity. It requires a few microns thick cell to absorb significant sunlight unlike crystalline silicon which requires over 100 microns thick cells. In addition to possessing a PCE of 29% which is the highest for any single junction PV cell [55], [73], GaAs cells are heat and radiation resistant. They possess a temperature coefficient p_{Max} of 0% which means no performance loss with respect to temperature rise from STC [56], [57]. However, GaAs cells fail to dominate the market with just about 1% of the market share as seen in Fig. 6. This is due to high cost. GaAs cells are limited to specialty applications where efficiency, performance under high temperature and radiation are favoured over cost[57], [72], [73]. Such applications include multi-junction PV cells, concentrated PV cells, satellites and demonstration solar powered cars.

2.3 State-of-the-art PV cells

These are the third generation PV cells. They are also termed emerging technologies because they are at experimental stage with little or no market significance. A large range of substances, mostly organic; often organo-metallic compounds are used. Sections 2.3.1 through to 2.3.6 discuss the most common 3rd generation PV cells.

2.3.1 Perovskite PV cells

Perovskite PV cells utilise thin film technology with thickness of <1 µm [74]–[76]. The manufacturing processes include a few steps and no sophisticated equipment. This makes the cells cheap to produce and simple to manufacture. Perovskite is more abundant in nature than silicon [77] which means availability of raw material is no contest. In addition to low cost, these cells are the fastest improving PV cells to date[74], [76], [78]. The first Perovskite PV cells were developed in 2010 and currently the PCE is above 15% [45], [74], [78], [79] and E-PBT is 2-3 months. The value is the shortest for any PV cell [80], [81]. Perovskite will make PV cells more affordable once commercialised. However, the technology has some shortcomings. The cells degrade quickly when exposed to the environment because they are made from organic materials [75], [76]. In addition, lead has been used in the cell to absorb sunlight which increases the technology's toxicity[75], [76], [79], [82].

2.3.2 Dye PV cells

Dye solar cells (DSC) and dye synthesized solar cells (DSSC) are thin film cells. The dyes possess photovoltaic properties and the manufacturing procedure does not require elaborate equipment. It is substantially easy to make. Thus the cells are cheap and can be manufactured utilising do-it-yourself (DIY) techniques[48], [83], [84]. Organic materials that are environmentally friendly which include fruits are used to make the cells. Dye PV PCE falls between 8-14% [45] and EPBT is 3 years [85]–[87]. Sadly, the cells are sensitive to air, moisture and temperature so they possess lifetime of 10 years [48], [88], [89]. They show poor performance at high temperatures and thus they are limited to low temperature and low light applications. The cells have the tendency to be corrosive and toxic.

2.3.3 Concentrated PV (CPV) cells

A concentrator is a PV cell designed to operate under illumination greater than 1 sun. Typically, the value ranges from 2 - 1000 suns and are characterised as low-to-high-concentration [90]–[92]. The operation involves that the incident sunlight is focused or guided by optical elements such that a high intensity light beam shines on a small PV cell with average surface area of 0.25 cm^2 [57][92], [93]. The short-circuit current from the PV cell depends linearly on light intensity. Thus, a device operating under 10 suns would have 10 times the short-circuit current as the same device under one sun operation [94]–[98]. Most concentrators use mirrors made from aluminium or plastic lenses to concentrate the beam of light onto a PV cell. Large mirrors are used to reflect sunlight to tiny highly efficient PV materials. GaAs is the principal material because the cells made from it can resist high heat dissipation characterising this technology [1], [40], [50], [51]. Less of the PV material and more of the mirrors are used to manufacture the CPV cell shown in Fig. 9. The inflatable aluminium-plastic composite mirrors are even cheaper[90], [99], [101]. The use of concentrators can increase the quantity of electric power by five-fold from typical operations [50], [92], [102], [101]. The savings in material enable the technology to achieve great decrease in unit price of electricity produced from the cell and lower the module price[5], [63], [92], [96], [101]. In addition to lower cost, concentrators have several potential advantages which include a PCE of up to 40% [50] and EPBT of 9 months. However, CPV cells require direct sunlight hence they are affected by shading.

2.3.4 Silicon Germanium (SiGe) PV cells

The continuous research to improve the PCE of silicon cells evolved a new technology. The technology utilises a new PV material which is a combination of silicon and germanium. Pandey et al [103] compared silicon cells to SiGe cells and discovered the latter possesses higher PCE. Their results show that a 5 µm thick SiGe cell is 11.3% efficient while a 10 µm thick Si cell is 11.8% efficient. In addition, SiGe cells show higher mechanical strength, higher electrical conductivity, lower recombination coefficient, higher minority carrier lifetime and higher optical performance [103]–[105]. Also, they possess lower module cost because the technology leads to material savings[103], [104], [106].

2.3.5 Nanofibre PV cells

These PV cells are an upgrade from regular thin film cells. They are highly flexible, semi-transparent and extremely light weight [50]. The cells are shown in Fig. 10. The materials used in the manufacture of nanofibre cell are majorly amorphous silicon, CIGS and CdTe. The technology is not faced with restriction to panels of particular dimensions and/or sizes. The cells can be installed on surfaces such as windows, walls, airplane wings and car screens - thereby transforming them into PV modules [107]. Although the technology has a PCE of 20% [85], nano PV cells are presently limited to low power applications.

Figure 9**:** Concentrated PV (CPV) cells [120]

Figure 10**:** Nano PV cells [167]

2.3.6 Multi-junction /Tandem /Cascaded PV Cells

This technology utilises multiple p–n junctions connected in series to create a PV cell by stacking different layers of semi-conductor materials. Most common materials used are gallium arsenide, amorphous silicon, micro-crystalline silicon and germanium. The p-n junction of each material produces electric current in response to different wavelengths of light [72], [108], [109]. Operating band gap energy range is 1.1 to 1.7 eV [50], [56], [94], [98]. The top cell material possesses the highest band gap and covers the highest absorption area [50] while underlying cells absorbs the section of the solar spectrum with smaller wavelengths. The use of multiple semiconducting materials allows the absorbance of a broader range of wavelengths thereby improving the PCE of the cell [105]. The technology possesses PCE of 45%. This is the highest values for any PV cell. Theoretically, an infinite number of p-n junctions would have a limiting efficiency of 86.8% under highly concentrated sunlight [50]. However, such technology would be very expensive with little or no commercial value[110], [111]. Currently, the technology is limited to space applications.

2.4 Section summary

The PV cell materials are summarised in this section. The sub-sections 2.4.1 and 2.4.2 discuss EPBT and PCE respectively, while the comparison of commercial PV cells is presented at sub-section 2.4.3. The section presents a recommendation of cell material for tropical climate applications at 2.4.4.

2.4.1 Energy payback time (EPBT)

Energy payback time (EPBT) of a PV cell is a measure of the performance of the technology/system. The EPBT quantifies how long it takes the system to recover all the energy that went into its manufacturing [43], [69], [112]. The EPBT is used here as a measure of commercial viability of the PV cell technologies. From the economic and business point of view, a consumer, who is eager to know when they will reap the benefits of investments, is provided a timeline by EPBT. Also, necessary comparisons can be made with fossil fuel energy sources. Figure 11 shows the plot of EPBT of some popular PV cells. The Figure shows that the best system in terms of EPBT is Perovskite cell which possesses 3 months EPBT [80], [81]. The value can be seen as the best for all PV cells. However, the commercial value is yet to be maximised. The CdTe cell is the second best with 8 months EPBT [43], [69]. This technology is the best for all commercial PV cells.

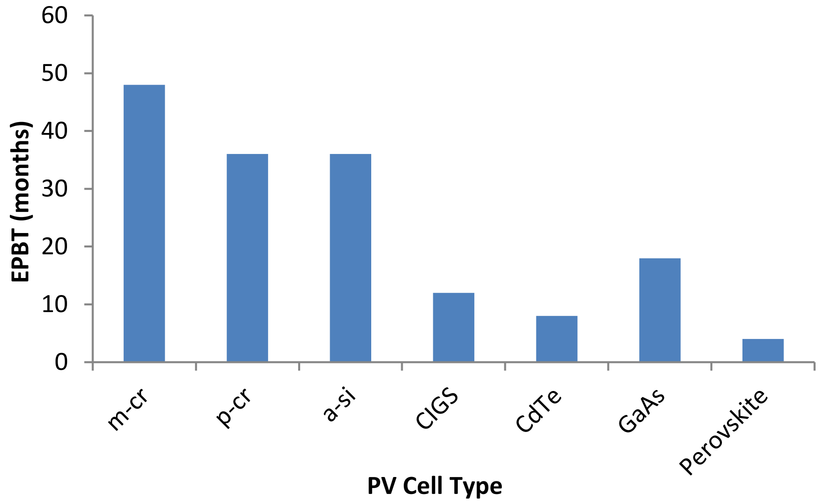


Figure 11**:** Energy payback time (EPBT) of popular PV cells.

2.4.2 Power conversion efficiency (PCE)

Fig. 12(a) shows maximum attained PCE of PV cells which have been discussed extensively in previous sections. The multi-junction PV cell with a PCE of 45% is the best of all PV cells. However, it should be noted that the commercial value is yet to be exploited. Fig. 12(b) shows maximum attained PCE for commercial PV cells. It can be seen in the Figure that mono-crystalline PV cell with PCE of 25% is the best for all commercial PV cells while the CdTe with PCE of 21% is the best for commercial thin film PV cells.

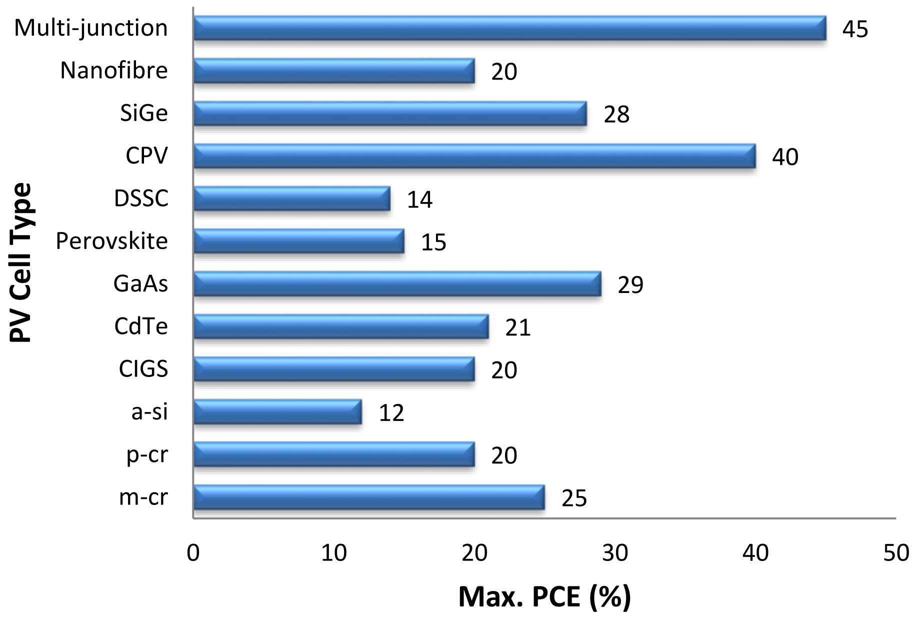


Figure 12a**:** Maximum attained PCE of PV cells

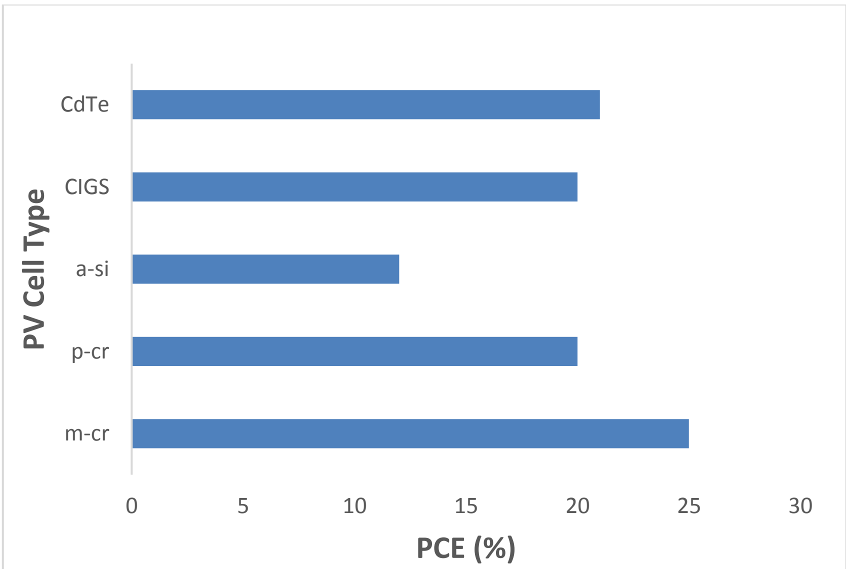


Figure 12b**:** Maximum attained PCE of commercial PV cells

2.4.3 Comparison of commercial PV cell materials

Table 1 presents the comparison of relevant properties of commercial PV cells. The factors used in the comparison include PCE, EPBT, performance under high-temperature and low irradiance, complexity of manufacturing process, carbon footprint and cost. It can be seen from the results presented in the table that the performance under high-temperature conditions of mono-crystalline and Poly-crystalline silicon PV cells decrease by 15% and 20% respectively while thin film cells are unaffected[55], [56] [47], [113]. The cell temperature coefficient p_{Max} which measures the percentage decrease in PCE with each degree rise in temperature from STC was also used to compare the PV cells performance. It is observed that p_{Max} of both mono-crystalline and poly-crystalline silicon PV cells are -0.5% while the amorphous silicon cell is -0.25% whereas CIGS and CdTe are both 0%[51], [52]. Under low irradiance conditions, the crystalline silicon PV cells demonstrate considerable power output reduction but there is negligible impact on power output for the thin film PV cells. The thin film PV cells possess lower cost ($/W) than the crystalline silicon PV cells. The cost per wattage of CdTe, CIGS, amorphous silicon, poly-crystalline and mono-crystalline are $0.7/W, $0.75/W, $0.8/W, $1.4/W and $1.6/W, respectively[46], [47], [114], [115]. In the case of limited space applications, the crystalline silicon PV cells are more suitable as they occupy a maximum of 9 m^2 for every 1 kW of power produced while the thin film cells cover a minimum of 9 m^2 per 1 kW power generated[114].

2.4.4 Recommendation

Based on the results and findings of this section, the CdTe PV cells are recommended for application in the tropics. The characteristics warranting the selection are presented thus. The cell:

- demonstrates PCE of 21% which is the highest for all commercial thin film cells.
- temperature coefficient of power output (p_{Max}) is 0%.
- High-temperature effect on PCE results to 0% drop.
- demonstrates negligible impact of low irradiance on power output.
- EPBT of 8 months which is the best for all commercial PV cells.
- cost of $0.7/W is the lowest for all commercial PV cells closest to the $0.5/W cost of fossil fuel energy sources.

It is important to note the CdTe PV cell demonstrates best performance in tropical climate while retaining its short EPBT and low cost.

Table 1: Comparison of commercial PV cell materials

Cell Type	Crystalline Silicon		Thin Film		
	Mono-crystalline	Poly-crystalline	Amorphous silicon	Cadmium Telluride	CIGS
Max. Efficiency	25%	20%	13%	21%	20%
High temp. effect on efficiency	15% drop	20% drop	0% drop	0% drop	0% drop
Temperature coefficient p_{Max}	-0.5%	-0.5%	-0.25%	0%	0%
Low irradiance performance	power output reduction	power output reduction	low impact on power output	low impact on power output	low impact on power output
Optimal Performance Temp.	performs well in cool weather but poorly in hot weather	performs well in cool weather but poorly in hot weather	performs well in cool weather, hot weather even in extreme heat	performs well in cool weather, hot weather even in extreme heat	performs well in cool weather, hot weather even in extreme heat
Surface area for 1kW power	7-9m^2	8-9m^2	13-20m^2	11-13m^2	9-11m^2
Cost ($/W)	1.6	1.4	0.8	0.7	0.75
Complexity of Manufacturing process	complicated, sophisticated and expensive	simpler and less expensive than mono crystalline	lower cost than crystalline silicon because less silicon required	lower cost and less sophisticated than crystalline silicon	lower cost and less sophisticated than crystalline silicon
Carbon Footprint (gCO_2-eq/kWh)	45	44	50	35	46
Energy Payback Time (EPBT) (months)	48	36	36	8	12
Market Availability	easily available and dominant	most dominant with largest market share	less dominant than crystalline silicon in the market	largest market for thin film	less dominant than crystalline silicon in the market
Environmental Effects	no known effects	no known effects	no known effects	elemental Cadmium is toxic	no known effects

3. Contact technologies

A contact attached to a PV cell is an electrical conductor that collects electrons and holes liberated in the PV material when exposed to photons [108], [116]–[118]. Contacts function to complete the circuit and enable electric current to flow from the PV cell to a load. Electrons are attracted to positively charged contacts while holes are attracted to negatively charged contacts. The contacts in an ideal PV cell exhibit complete selectivity [6], [72], [112], [114], [119]. Thus, while electrons migrate to one contact, the holes migrate to the other contact. Unfortunately, this situation is different from an actual PV cell where recombination of electrons and holes occur. Recombination is a process in which the electrons recombine with the holes before they can be conducted away as electric current. There is ongoing research to increase the performance of PV modules by improving selectivity of contacts and reducing recombination to the barest minimum [120]–[122].

Sections 3.1 and 3.2 present design considerations of contacts and types of contacts respectively while discussions on recommendations of contact technology for tropical climate application are at section 3.3.

3.1 Design Considerations

In order to improve PV module performance in tropical climate, the choice of suitable contacts is vital. In contact selection, certain design factors are considered. Desired qualities of contacts include high thermal conductivity, high electrical conductivity and low resistivity [123]–[125]. Additionally, a contact acts as a support/reinforcement for the PV cell thereby increasing the assembly strength. Thus, the contact material should possess good mechanical strength in addition to the high quality electrical and thermal properties [79], [116], [117], [125], [126].

Sections 3.1.1, 3.1.2 and 3.1.3 discuss in detail the mechanical, thermal and electrical design considerations of contacts respectively.

3.1.1 Mechanical Properties

PV interconnection (contacts, solder and ribbon interconnects) is made from different materials with distinctive properties. Thus, the interconnection experiences a mismatch of coefficients of thermal expansion (CTE) of the different materials in the interconnect assembly. Material expansions at different rates introduce mismatch related degradation in the joint. The contact which possesses a greater CTE will expand more than the ribbon interconnects with lower CTE. Figure 13 shows the interconnection under flexural loading occasioned by the differential linear expansion CTE mismatch of bonded materials. Thermal stress is induced in the interconnection.

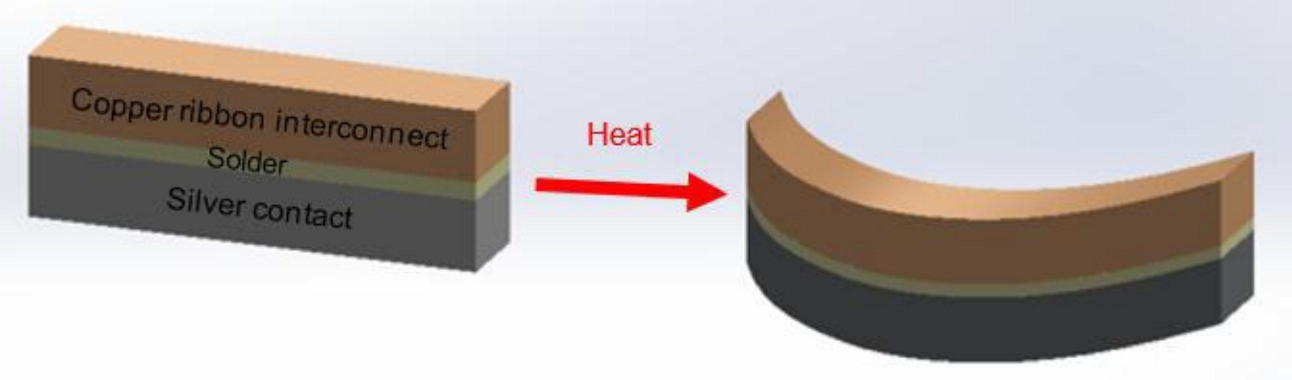


Figure 13: PV interconnection showing effect of different rate of material expansion

$$\Delta L = \alpha L dT \tag{1}$$

$$\varepsilon = \frac{\Delta L}{L} \tag{2}$$

Combining (1) and (2),

$$\varepsilon = \alpha dT \tag{3}$$

$$\sigma = E\varepsilon \tag{4}$$

Where ΔL is expansion and L is initial length (metres). α is the CTE (K^{-1}), dT is temperature rise (K), ε is deflection, σ is stress and E is Young's Modulus (Pascal). Equation (1) through (3) presents the relationship between temperature rise (dT) and deflection (ε). It is observed that with each degree rise in temperature, deflection increases. Equation (4) shows stress (σ) is directly proportional to deflection. This implies stress increases as temperature rises. In order to assure thermo-mechanical reliability PV interconnections, materials with very close values of CTE are recommended for use.

3.1.2 Thermal Properties

Operations in tropical climate increase the range of operating temperature of the module. This impacts on the quantity of heat accumulated in the materials bonded together in the interconnection. Recalling the relationship between the parameters as:

$$Q = mcdT \tag{5}$$

where Q is quantity of heat (Joules), m is mass (kg) of the material and c is the specific heat capacity ($JK^{-1}kg^{-1}$).

Equation (5) presents the relationship between temperature rise (dT) and quantity of heat (Q) accumulated in the system. It is observed that with each degree rise in temperature, there is an increase in heat. Heat accumulation in PV modules negatively impacts the PCE, PO, thermal reliability and performance. To achieve good heat management through efficient heat dissipation, high thermal conductivity is a desired property for contacts.

3.1.3 Electrical Properties

It is a basic knowledge that as the temperature of a material increases, its resistivity increases while electrical conductivity decreases. As temperature rises, electrons are thermally agitated and energized. Thus, they vibrate and collide with one another and this activity increases their resistance to flow as electric current. Consequently, high resistivity is not a desired quality for a contact. In the tropical climate where temperatures are high, the resistivity of contacts is also high.

$$\rho = \rho_0 \, [1 + \alpha(dT)] \quad (6)$$

$$R \propto \rho \quad (7)$$

$$R = R_0 \, [1 + \alpha(dT)] \quad (8)$$

$$I = \frac{V}{R} \quad (9)$$

$$P = I^2 R \quad (10)$$

Where ρ_0 is initial resistivity (Ωm), ρ is final resistivity (Ωm), R_0 is initial resistance (Ω), R is final resistivity (Ω) and α is temperature coefficient of resistivity (K^{-1}). I is electric current (amp.), V is voltage (volts) and P is electrical power (watts).

Equation (7) shows resistance is directly proportional to resistivity. In tropical climate where temperature conditions are higher than the STC, with each degree rise in temperature, there is a corresponding increase in resistivity and resistance. Equation (6) presents the relationship between temperature rise (dT) and resistivity (ρ) while Equation (8) presents that between temperature rise (dT) and resistance (R). Equation (9) demonstrates that at constant voltage (V), an increase in resistance (R) results in electric current (I) decrease. Additionally, any decrease in electric current leads to decrease in electrical power generated by the PV cell. Equation (10) shows the relationship between electric current and electric power. Thus, PV cells/modules operating in the tropics tend to generate low magnitude of electric current which leads to low power output and low performance.

3.2 Types of Contacts

The sections 3.2.1, 3.2.2 and 3.2.3 discuss the different types of contact technologies used in PV module manufacture. These include the front-to-back, back/rear and buried contacts technologies respectively. Section 3.3 discusses recommendations on contact technology for tropical climate application.

3.2.1 Front-to-back contact

This is the most common type of contacts used in PV cells [40], [118]. In this type of arrangement, one contact is placed at the front of the cell and the other is placed at the back [46], [112], [117]. The architecture is shown in Fig. 5. The front contact is attached on the face of the cell and thus shades that part of the cell. This arrangement reduces the surface area of the cell exposed to direct sunlight. Consequently, the module power output and cell performance are adversely affected by shading losses [96], [103], [122], [127]. The interconnection is from front to back of the cell with noticeable space between them as seen in Figs. 16 and 17. This architecture is susceptible to fatigue failure and recombination losses in the cell.

3.2.2 Back/Rear contacts

This type of contact is an improvement of the conventional front-to-back contact [57], [92], [96], [128]. Both contacts are placed at the back of the cell which increases the surface of cell exposed to direct sunlight. The arrangement eliminates shading on the front of the cell. Rear contact PV cells achieve potentially higher efficiency by moving all or part of the front contact grids to the rear of the device [122]. They are especially useful in high current cells such as concentrators or large areas. An additional benefit is that with both contacts on the rear, cells are easier to interconnect and can be placed closer together in the module since there is no need for a space between the cells as seen in Fig. 14. Recombination losses are reduced [103], [122], [106].

3.2.3 Buried Contacts

In order to overcome some disadvantages of the conventional front-to-back contacts, buried contacts were introduced to replace the front contacts. Buried contacts are achieved by cutting a series of trenches in the top surface of the PV material with either a laser or a mechanical saw. The architecture of buried contact technology is shown in Fig. 15. The trenches which are about 30 µm wide and 80 µm deep are filled up using electroplating process. The deposited metal, usually copper, using the plating process is the contact [121], [127], [129]–[131].

This type of contact allows for a large metal height-to-width aspect ratio. A large metal contact aspect ratio in turn allows a large volume of metal to be used in the contact finger, without having a wide strip of metal on the top surface. Therefore, a high metal aspect ratio allows a large number of closely spaced metal fingers, while still retaining a high transparency and low resistive losses. For example, on a large area device, a front-to-back contact cell may have shading losses as high as 10 - 15%, while in a buried contact structure, the shading losses will only be 2 - 3%[46][121], [130], [131]. These lower shading losses allow low reflection and therefore higher short circuit currents. Furthermore, a buried contact structure includes a self-aligned, selective emitter, which thereby reduces the contact recombination and also contributes to high open circuit voltages and short circuit currents.

This technology improves the performance of PV cells by up to 25% when compared with the conventional front-to-back contacts [121], [129], [131]. The efficiency advantages of buried contact technology provide significant cost and performance benefits. In terms of $/W, the cost of a buried contact solar cell is the same as a screen-printed front contact in a PV cell [120]. However, due to the inclusion of certain area-related costs as well as fixed costs in a PV system, a higher efficient solar cell technology results in lower cost electricity. An additional advantage of buried contact technology is that it can be used for concentrator systems [121]. The interconnection goes from front to back as in front-to-back contacts. Shading losses though reduced are present as well as recombination losses.

3.3 Section summary and recommendations

The back contact technology is recommended for tropical climate operation because it results in higher power output, higher PCE, easy and reliable interconnection as well as reduced recombination loss [49], [92], [122], [125], [132].

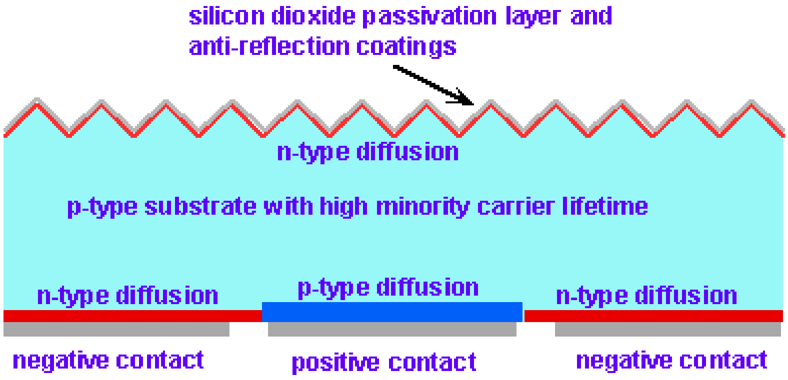


Figure 14: Back contact solar cells [116]

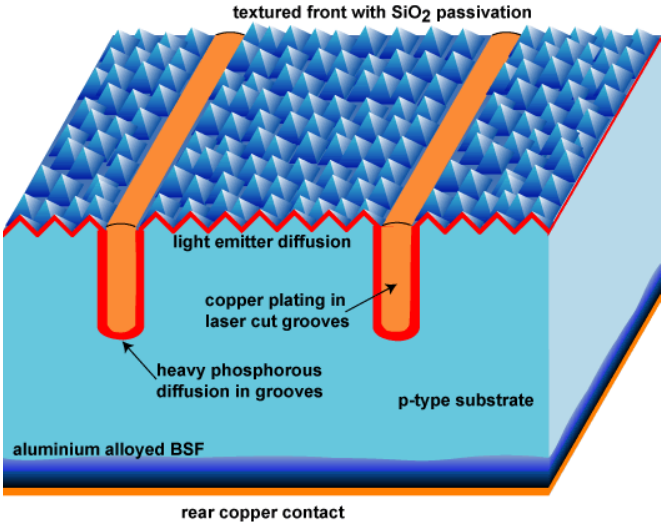


Figure 15: Buried Contact [120]

4. Interconnection technologies

The PV module interconnection is made up of the solder and the ribbon as seen in Figs. 16 and 17. Solder is used to join contacts and ribbon interconnects. The ribbon is used to connect one cell to another to amplify voltage and power output. The configuration forms a module assembly [117], [119], [133]–[136]. PV cell interconnect occurs when individual PV cells are joined. Usually about 6 - 10 cells are joined in a cluster. This architecture is frequently referred to as cell stringing. In PV module assembly, these interconnected PV cell clusters are joined together to produce a complete PV module. There are typically 20 – 80 PV cells in a module. This is frequently referred to as cell bussing [61].

The ribbon interconnects are usually made of copper while the solder materials are made from the various lead-free solders. The solder alloy composition is discussed in section 4.1. The materials, ribbon bonded with the silver contacts in the interconnection, possess different coefficient of thermal expansion. At elevated temperature, the differential material expansion mismatch induces thermal stresses on the interconnection which culminates in fatigue loading occasioned by the environmental temperature cycle history. Consequently, the interconnection surfers delamination, crack initiation, propagation and rupture [126], [137]–[142]. Interconnection degradation has been reported by [117][143], [144] as causing over 40% of PV failures and this figure is greater in the tropical climate. Thus, there is the need to mitigate this challenge by investigating interconnection degradation mechanism to increase prediction accuracy of lifecycle of solder interconnections in various environments and climates. This will increase the operational reliability of PV module interconnections especially in the tropics. It has also been reported that interconnection degradation contributes to increase in series resistance of PV modules which decreases their power output [126], [137], [138], [141], [145].

Section 4.1 discusses the solder material while section 4.2 examines interconnection technologies and materials with the focus of identifying suitable technologies with potential of improving PV module performance in tropical climate.

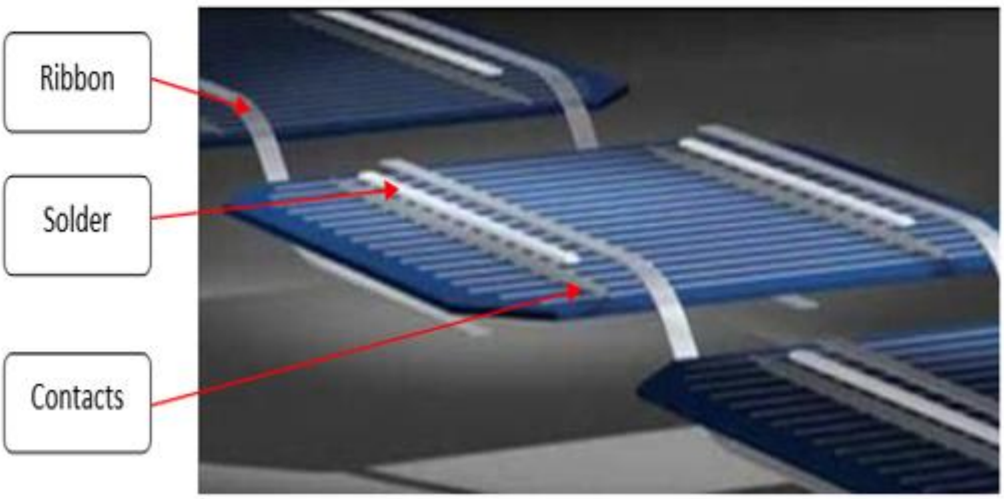


Figure 16: showing cell, contacts and interconnection [159]

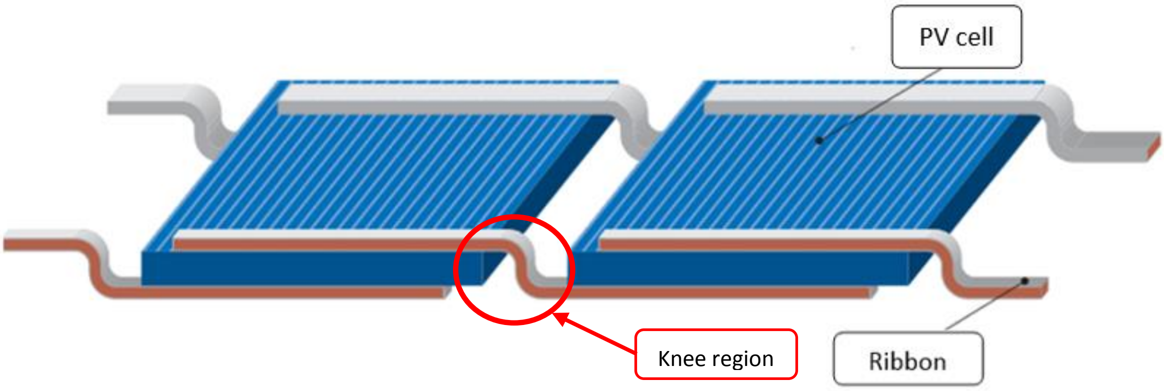


Figure 17: Front-to-back interconnection[157]

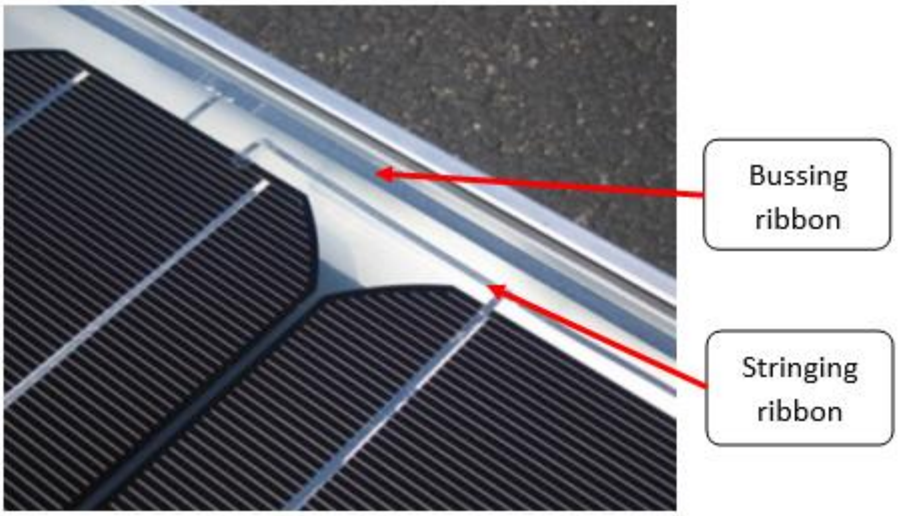


Figure 18: Ribbon Interconnects[61]

4.1 Solder material

In the PV module assembly, solder joins the ribbon interconnects to the contacts. Solder materials composition include SnAgCu (SAC) which is the most common. Other compositions are AuGe. For a SAC solder composition, increase in silver content leads to increase in elastic modulus, thermal induced stress, accumulated strain energy and fatigue life as well as a decrease in accumulated plastic work [136]. Thus, the alloying composition of constituent solder material plays a key role in the nature of the PV interconnect degradation.

4.1.1 Lead free solder

Prior to the Restriction of Hazardous Substances (RoHS) directive by the European Union (EU) which took effect in June 2006, lead based solders which include SnPb were used in the manufacture of the majority of electrical and electronic devices [64], [66], [146]. In the PV industry, lead based alloys were used for various interconnection technologies [147]. Currently, there is a shift from lead-based alloys to lead-free alloys because of the environmental impacts of lead, globally [144], [65], [148], [149]. More and more lead-free solders are being developed to substitute lead based solders [141], [142], [150]–[152]. The tin-silver-copper (SnAgCu or SAC) solder alloys have been reported to be the best alternative for eutectic SnPb solder in the PV industry [144], [153]. Section 4.1.2 focuses on the thermo-mechanical reliability of mainstream SAC solder alloys which include SAC305, SAC405 and SAC387.

4.1.2 Thermo-mechanical reliability of solder interconnection

PV solder joint damage has been reported by numerous studies including [117], [125], [135], [113], [154] as responsible for over 40% of PV module failures and this figure is higher in the tropical climate. Degradation of solder interconnections is due to the coefficient of thermal expansion (CTE) mismatch between bonded materials - silver contacts, solder and copper ribbon. During the operation of PV modules in the tropical climate, temperature rises from the STC to as high as 90°C and then falls after some time. This repeated temperature cycle induces thermo-fatigue failure of the solder joint which begins with solder cracking. This phenomenon accounts for the higher PV failure rates in the tropics.

4.2 Ribbon interconnection

Photovoltaic ribbons are prevalently made of solder-coated copper. They possess high electrical conductivity and low yield strength making them “deadly soft” [61], [125], [155]–[157]. There are majorly two types. These are shown in Fig. 18. The cell interconnect ribbon, also called ***stringing*** ribbon, connects individual cells to one another in a cluster and delivers current to the ***bussing*** ribbon. Stringing ribbon is typically 2 mm wide. For PV module assembly, interconnected PV cell clusters are joined together using 5 mm wide tabbing ribbon, also called bussing ribbon. Bussing ribbon delivers current to the module's junction box for final power output [60].

The sections 4.2.1 and 4.2.2 discuss the different types of interconnection technologies used in PV module manufacture. These are the front-to-back and back-to-back interconnection technologies respectively. Section 4.3 discusses recommendations on interconnection technology for tropical climate application.

4.2.1 Front-to-back interconnection

As can be seen in Figs. 16 and 17, the stringing ribbon originates from the front of one cell and terminates at the back of the next cell. As the name implies, this architecture form a string in the PV module. The configuration is used for front-to-back and buried contact PV cells which have been extensively discussed in sections 3.2.1 and 3.2.3, respectively. The arrangement results in reduced power output and PCE of the PV module assembly. Owing to existing gap between connected cells, the technology is challenged with recombination losses. Front-to-back interconnection technology is characterised by "**knee**" regions which are highly susceptible to fatigue loading[125], [140], [143]. They are found to be the critical point of fatigue failure[60], [143]. The knee region is shown in Fig. 17.

4.2.2 Back-to-back interconnection

As can be seen in Fig. 14, the stringing ribbon connects the back of one cell to the back of the next until all the cells in the module and connected. This type of interconnection are found in back contact PV cells where there is no ribbon interconnect on the face of the PV cell. It ensures the maximum cell surface area is exposed to direct sunlight. Less of ribbon material is used and the technology has a higher packing density as well as reduced recombination losses when compared with front-to-back interconnection[122], [158]. Moreover, the fatigue failure critical points are eliminated which improves the thermo-mechanical reliability of the interconnection and hence the PV module[117], [147], [159].

4.3 Section summary and recommendation

Owing to low recombination losses, longer fatigue life and better thermo-mechanical reliability of back-to-back interconnection technology, the technology is recommended for use in the manufacture of modules which are designed to operate in tropical climate as they are projected to possess enhanced thermo-mechanical reliability.

5. Summary and recommendations

This review has presented an investigation which focuses on identifying the suitable cell, contact and interconnection technologies which have potential of producing a robust PV module that can operate with enhanced performance in tropical climate. The results and findings of the critical review identifies a module technology comprising CdTe cell, back contacts and back-to-back interconnection as poised to have the characteristics and potential for improved performance at elevated temperature typical of tropical ambient. The technology is therefore recommended to be used to assemble PV module for tropical climate applications.

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